

# MINERvA Medium Energy Publication Plans

The MINERvA Collaboration

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## 1 Introduction

MINERvA has three overarching goals for the physics legacy of its Medium Energy data. These goals are primarily oriented towards helping other experiments make more accurate neutrino oscillation measurements, but in the meantime we will also learn a great deal about the nuclear environment.

These goals can be characterized as follows:

- Measurements of Neutrino Interactions and antineutrino interactions that are of interest to the oscillation community, with a focus on understanding the role of the nuclear environment on those interactions so we are ready when DUNE turns on with its argon target. By studying interactions off different nuclei we can help better resolve differences between initial-state nucleon dynamics with the nuclear environment and final-state interactions of the resulting particles. Distinguishing between these two is important to better understand both neutrino energy reconstruction and lepton identification.
- Tests of techniques that will be of use to DUNE to reduce their flux systematics (i.e. nu-e scattering [1] and low hadronic recoil events) and development of techniques that inform DUNE near detector design (e.g. transverse kinematic imbalance (TKI) [2, 3, 4, 5] and low recoil analysis technique).
- Creation of a library of well-measured neutrino and antineutrino interactions that allows access to our data as a resource to address surprises in the DUNE era.

## 2 Current Status of Medium Energy Data and Publications

As of this writing the experiment has processed and calibrated the data from both the neutrino and antineutrino runs, and has finished generating the simulations of the neutrino data and over three quarters of the antineutrino data. Because we generate between 2 and 10 times the data statistics this is the bulk of our computing usage since we completed taking the antineutrino data in February 2019.

The MINERvA data set represents a high-volume library of neutrino and antineutrino interactions across a broad energy range and a broad range of nuclei. The ability to make accurate measurements of neutrino to antineutrino differences is particularly important for DUNE's goal of measuring CP violation. The MINERvA Detector has well-understood event reconstruction and particle identification, and will be of interest to the HEP community well after MINERvA ceases to be an active collaboration. The experiment is therefore devoting significant effort to a Data Preservation project that will facilitate MINERvA physics analyses well after 2022 by unifying the common elements of cross section measurements, and simplifying the way the data and simulation are accessed. The final product will include data from and simulations of both the Low Energy (2009-2012) and Medium Energy (2013-2019) neutrino and antineutrino data sets. Several of the publications that will occur before 2022 will also be done using the output of the Data Preservation effort. This output will be made available to the broader HEP community to enable analyses to be done well into the DUNE era.

As of this writing MINERvA has published two results on the Medium Energy neutrino data: one that measures neutrino-electron scattering in order to constrain the NuMI flux that underlies all of our future publications [6], and one that measures the charged-current process where only a muon and nucleons are created [7], a process that makes up the majority of interactions that are selected in the current generation of accelerator-based neutrino oscillation experiments.

### 3 Overview of Neutrino Interactions

The only two interaction channels which have sub per cent cross section uncertainties are neutrino scattering off electrons in the target: neutrino-electron scattering ( $\nu(\bar{\nu}) + e^- \rightarrow \nu(\bar{\nu}) + e^-$ ) and inverse muon decay ( $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ ). MINERvA uses these two channels to measure the flux of neutrinos through the detector, which in turn is used to measure cross sections for many other channels. Models of these other channels all carry significantly higher uncertainties, associated with both the primary neutrino-nucleon interaction and subsequent final state interactions. The channels that the MINERvA collaboration have targeted as priority measurements are briefly summarized below.

The process where no pions are produced in charged-current interactions is the primary signal process in T2K and NOvA, but as the neutrino energy rises, so does the range of energy that can be transferred to the nucleus. So while most attention lately has been put on the “zero pion” channel, that level of attention must turn to processes with higher momentum transfers. We outline here the different channels that are accessible in the MINERvA Medium Energy data.

#### 3.1 Charged Current Quasielastic-like Interactions

These are the events that make up the bulk of T2K events, a third of NOvA events, and are the ones for which T2K has the best neutrino energy reconstruction so most of the theoretical activity has been focused there. Because of the relatively simple topology of this channel, there is information in measurements of kinematic variables projected to the plane transverse to the incident neutrino direction [8, 9]. These TKI variables help to disentangle the effects of final state and initial state interactions, which have different implications for neutrino energy reconstruction.

#### 3.2 “Low Recoil” Charged Current Interactions

These events in the Low Energy beam gave us our first glimpse into multinucleon correlations, and a similar analysis has been adopted by NOvA to do the same at their neutrino energy and detector composition. Understanding the energy dependence of these multinucleon effects is important, and the remaining discrepancies we see point to problems with the way we model pion production in neutrino interactions.

Neutrons play a key role in oscillation experiments because they take away energy from the initial neutrino but their energies are not well-measured. Scintillator has better neutron identification than Ar because of the hydrogen, so we are working to use the signatures we do have of neutrons to get their directions and locations, and in some cases even an energy proxy since we can measure time and distance for neutrons.

#### 3.3 Charged Current Pion Production

Neutrino Interaction Channels with single pions make up a significant fraction of NOvA events, they are a new signal sample that T2K is using to gain statistics, and will be an even larger fraction of the DUNE far detector event sample. We have yet to understand the role of multi-nucleon correlations in pion production, and other nuclear effects are likely to be even more important than in interactions without pion production. Neutral pion production is also the source of background to electron neutrino and antineutrino appearance, so those are important for yet a different reason. Kinematic variables measured relative to the plane that is transverse to the neutrino direction (TKI) can again help distinguish between initial and final state effects [10].

Coherent pion production is a subset of pion production channels, where a neutrino scatters coherently over the entire nucleus, imparting very little momentum, but creating a charged or neutral pion. The neutral pion channel is a rare but poorly constrained background to electron neutrino appearance. The dependence of this cross section on target nucleus has yet to be measured but is accessible in MINERvA’s data.

#### 3.4 Shallow Inelastic Scattering

This is a region with very little theoretical understanding, and is bridge the region between the resonant production we are just starting to understand and the Deep Inelastic Scattering which we think we do understand at at very high momentum transfers.

### 3.5 Deep Inelastic Scattering

We want to understand if the EMC effect [11, 12] exists in neutrinos and antineutrinos. We began this investigation in our Lower Energy data set that was collected between 2010-2012 but the result was severely limited by statistics [13]. The Medium Energy exposures should finally get us to our few per cent statistical precision on the one-dimensional cross sections as a function of Bjorken  $x$ .

## 4 MINERvA Collaboration

The MINERvA Collaboration spans students, postdocs, professor and scientists from (currently) 23 Universities and one national Laboratory. Of the 23 University groups, 12 are domestic and of those, 6 are funded by the Department of Energy-HEP and 3 by the National Science Foundation-HEP. This document is a snapshot of that collaboration as of November 9, 2020; we are in the process of welcoming two new institutions to the collaboration this month. There is a significant Latin American and Indian contingent on MINERvA who have also joined DUNE. The table below shows the institutions who currently have graduate students and/or postdoctoral researchers who are working on physics analyses on MINERvA.

Aligarh Muslim University (AMU)	Centro Brasileiro de Pesquisas Físicas (CBPF)
Fermi National Accelerator Laboratory (FNAL)	University of Florida (UF)
Universidad de Guanajuato (GTO)	IISER Mohali (IISERM)
University of Minnesota – Duluth (UMD)	Oregon State University (OSU)
University of Oxford (Ox)	University of Pennsylvania (Penn)
University of Pittsburgh (Pitt)	Pontificia Universidad Católica del Perú (PUCP)
University of Rochester (Roch)	Universidad Técnica Federico Santa María (USM)
Tufts University (Tufts)	William & Mary (W&M)

Table 1: Institutions and abbreviations on MINERvA

## 5 Conclusions

MINERvA has already published 32 different cross section results on its Low Energy data set, and Table 2 is a table of over 30 neutrino interaction analyses that are currently underway whose results we expect to be finalized by the end of 2022. The institutions whose students and postdocs that are most active on each analysis are also provided. Table 3 shows a table of potential analyses that have yet to begin but which could yield interesting physics results in a longer timescale, and the institutions that plan to lead those analyses.

## References

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Interaction Type	Analysis Topic	Institution(s)
$\nu$ and $\bar{\nu}$ Flux Constraints	$\nu$ -Electron Scattering (published) $\bar{\nu}$ -Electron Scattering Low and High “nu” fluxes, $\nu$ mode Inverse Muon Decay	FNAL, W&M W&M, Rutgers Roch Roch
Quasielastic-like	$\nu_\mu$ on CH: 2-d muon kinematics (published) $\nu_\mu$ on CH: 3-d muon and proton kinematics $\nu_\mu$ on CH: 2-d and 3-d muon TKI $\bar{\nu}_\mu$ on CH 2-d muon kinematics $\nu_\mu$ on Pb,Fe,H <sub>2</sub> O,C $\bar{\nu}_\mu$ on Pb,Fe,H <sub>2</sub> O,C $\nu_\mu$ Two-proton production on CH $\nu$ and $\bar{\nu}_\mu$ neutron production on CH	OSU, Roch Roch Ox, Roch, FNAL OSU Roch Penn Tufts Roch
Low Recoil	$\nu_e$ and $\bar{\nu}_e$ on CH $\nu_\mu$ on CH $\nu_\mu$ Energy Dependence on CH $\nu_\mu$ with $\pi^+$ tag $\nu_\mu$ neutron production	Pitt, Roch UMD, PUCP UMD Roch, GTO Roch
Pion Production	$\nu_\mu \pi^\pm$ on CH $\nu_\mu \pi^\pm$ on H (TKI) $\nu_\mu \pi^\pm$ on Pb,Fe,H <sub>2</sub> O,C $\nu_\mu$ Coherent $\pi^+$ on Pb,Fe,H <sub>2</sub> O,C $\nu_\mu \pi^0$ on CH $\nu_\mu \pi^0$ on Pb,Fe $\nu_\mu$ Diffractive $\pi^+$ on CH NC $\pi^0$ on CH	Pitt, GTO Ox Roch GTO USM Roch Roch Tufts
Shallow Inelastic Scattering	$\nu_\mu$ and $\bar{\nu}_\mu$ on Pb,Fe,C, CH Machine Learning Identification	CBPF CBPF
Deep Inelastic Scattering	$\nu_\mu$ on Pb,Fe,C, CH $\bar{\nu}_\mu$ on Pb,Fe,C, CH	W&M, UF, AMU AMU, W&M
Inclusive $\nu_\mu$ Charged Current Scattering	$\nu_\mu$ on CH $\nu_\mu$ Multiplicity using ML $\nu_\mu$ on Pb (DSECAL) $\nu_\mu$ on Pb,Fe,C $\nu_\mu$ on He Low “nu” Cross Section	Roch GTO GTO, W&M UF, W&M UF Roch

Table 2: Summary of Analyses on MINERvA whose planned publication dates are before the end of 2022. Channels are charged current processes unless indicated in line.

	<b>Analysis Topic</b>	<b>Institution</b>
<b><math>\nu</math> and <math>\bar{\nu}</math> Flux Constraints</b>	Low "nu" flux, $\bar{\nu}$ mode	
<b>Quasielastic-like</b>	3-dimensional $\bar{\nu}_\mu$ on CH Carbon De-excitation (JINST) $\nu_e$ and $\bar{\nu}_e$	UMD
<b>Pion Production</b>	$\bar{\nu}_\mu$ Coherent $\pi$ on Pb,Fe,H <sub>2</sub> O,C $\bar{\nu}_\mu \pi^\pm$ on CH $\bar{\nu}_\mu \pi^\pm$ on Pb,Fe,H <sub>2</sub> O,C	
<b>Deep Inelastic Scattering</b>	$\nu_\mu, \bar{\nu}_\mu$ Structure Functions on Pb,Fe,C, CH	AMU, W&M
<b>Inclusive <math>\nu_\mu</math> Scattering</b>	$\bar{\nu}_\mu$ on CH and $\bar{\nu}/\nu$ Ratios $\bar{\nu}_\mu$ on Pb,Fe,C, CH $\nu_e$ and $\bar{\nu}_e$	W&M, Roch
	Interactions with range out muons $\bar{\nu}_\mu$ on Pb (DSECAL) Low "nu" Cross Section in $\bar{\nu}$ Mode	GTO, W&M
<b>Model Tuning</b>	Global Tune based on MINERvA's QE-like and Resonance Measurements	
<b>Neutral Current Interactions</b>	NC elastic in CH, C, Pb, Fe NC $\pi^0$ production in CH, C, Pb, Fe NC charged pion production in CH, C, Pb, Fe	
<b>Beyond the Standard Model</b>	Searches for Dark Matter ("late" neutrino events) Short Baseline Oscillations (using $\nu$ -e constraint)	

Table 3: Summary of Potential Analyses on MINERvA whose publication dates would be after 2022. Channels are charged current processes unless indicated in line.